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Fire Safety in Space – Beyond Flammability Testing of Small Samples

Grunde Jomaas: Technical University of Denmark, Kgs. Lyngby, Denmark

Jose L. Torero: University of Queensland, Brisbane, Australia

Christian Eigenbrod: University of Bremen (ZARM), Bremen, Germany

Justin Niehaus, NASA Glenn Research Center, Cleveland, OH, USA

Sandra L. Olson: NASA Glenn Research Center, Cleveland, OH, USA

Paul V. Ferkul, Universities Space Research Association, Cleveland, OH, USA

Guillaume Legros: Université Pierre et Marie Curie, Paris, France

A. Carlos Fernandez-Pello: UC Berkeley, Berkeley, CA, USA

Adam J. Cowland: University of Edinburgh, Edinburgh, UK

Sebastien Rouvreau: Belisama R&D, Toulouse, France

Nickolay Smirnov: Moscow Lomonosov State University, Moscow, Russia

Osamu Fujita: Hokkaido University, Sapporo, Japan

James S. T'ien: Case Western Reserve University, Cleveland, OH, USA

Gary A. Ruff: NASA Glenn Research Center, Cleveland, OH, USA

David L. Urban: NASA Glenn Research Center, Cleveland, OH, USA

Abstract

An international research team has been assembled to reduce the uncertainty and risk in the design of spacecraft fire safety systems by testing material samples in a series of flight experiments (*Saffire 1, 2, and-3*) to be conducted in an Orbital Science Corporation Cygnus vehicle after it has undocked from the International Space Station (ISS). The tests will be fully automated with the data downlinked at the conclusion of the test before the Cygnus vehicle re-enters the atmosphere.

The unmanned, pressurized environment in the *Saffire* experiments allows for the largest sample sizes ever to be tested for material flammability in microgravity, which will be based on the characteristics of flame spread over the surface of the combustible material. Furthermore, the experiments will have a duration that is unmatched in scale compared to earth based microgravity research facilities such as drop towers (about 5 seconds) and parabolic flights (about 20 seconds). In contrast to sounding rockets, the experiments offer a much larger volume, and the reduction in the oxygen concentration during the *Saffire* experiments will be minimal.

The selection of the experimental settings for the first three *Saffire* experiments has been based on existing knowledge of scenarios that are relevant, yet challenging, for a spacecraft environment. Given that there is always airflow in the space station, all the experiments are conducted with flame spread in either concurrent or opposed flow, though with the flow being stopped in some tests, to simulate the alarm mode environment in the ISS and thereby also to study extinguishment. The materials have been selected based on their known performance in NASA STD-6001Test-1, and with different materials being classified as charring, thermally thin, and thermally thick. Furthermore, materials with non-uniform surfaces will be investigated.

Keywords: Flame propagation, microgravity, fire safety, experiments, flammability.

* grujo@byg.dtu.dk

Telephone: +45 20 19 87 72

Fax: +45 45 88 32 82

Introduction

Virtually every type of enclosure that houses people (cars, trains, ships, planes, buildings, mines, and tunnels) has been the subject to relevant full scale fire testing. In comparison, no such testing has occurred for manned spacecraft, mainly due to the complexity, cost and risk associated with operating a long duration fire experiment of a relevant size in microgravity. Therefore, the entire body of low-gravity fire research has either been conducted in short duration ground-based microgravity facilities [1, 2, 3, 4] or has been limited to fuel samples of the order of 10 cm in dimension [5-11]. Despite the fact that the work conducted to date has shown that fire behavior in low-gravity is very different from that in normal-gravity, with differences observed for flammability limits, spread behavior, color and structure [2, 4, 7-11], no material flammability or fire tests in microgravity have been conducted at an appropriate scale for adequate safety design and model development. Furthermore, contrary to upward spread in normal gravity, where flame growth is normally observed, modeling results in concurrent purely forced flow in zero gravity suggests a limiting flame length depending on the velocity magnitude [12]. However, this can only be verified through a larger scale test.

Therefore, the current assumptions of safety based on normal gravity tests and protocols and extrapolated to microgravity on the basis of modelling tools can be expected to carry significant uncertainty [13]. Furthermore, all existing scaling tools that enable extrapolation of empirical results to real microgravity performance have been challenged by the emergence of phenomena normally ignored because they are masked by buoyancy [14].

The Spacecraft Fire Safety Demonstration Project aims to overcome some of the current shortcomings in the understanding of fire safety in microgravity. It is run by scientists from NASA and an international group of scientists that wants to improve spacecraft fire safety designs for next-generation space vehicles and habitats. This will be accomplished not only by formulating and conducting a low-gravity fire safety experiment on a scale – both in duration and size – that is relevant for spacecraft, but also by developing and demonstrating next-generation fire safety instrumentation and predictive tools to guide future spacecraft designers and crew members.

The main effort of the project is the development of the Spacecraft Fire Experiment (*Saffire* 1-3) hardware, supported by the NASA Advanced Exploration Systems Program and ESA-supported development efforts, and seek to address this knowledge gap through the use of an unmanned, but

pressurized, cargo transfer vehicle (Cygnus from Orbital Sciences) after it has completed its supply mission to the International Space Station. The experiments, which have undergone rigorous safety testing [15] are large-scale material flammability demonstrations that will facilitate the understanding of the long-term consequences of a potential spacecraft fire and provide data not only for the verification of detailed numerical models of such an event but also for the development of predictive models that can assist and optimize fire prevention, response and mitigation. Furthermore, the experiments will examine fire behavior on a scale that is relevant to spacecraft fire safety concerns and will also provide an unprecedented opportunity to expand the understanding of the fundamentals of fire behavior in low-gravity.

Background for Experimental Design

Fire is a complex phenomenon that involves numerous fields of expertise from material sciences to thermo-fluid-mechanics and chemistry. Furthermore, it involves time and length scales that span orders of magnitude and that are intimately coupled, resulting in different processes dominating at different scales and different times [16]. Thus, the predictive description of fire phenomena is extremely difficult and limited to very simple scenarios. In complex systems such as spacecraft, this is all the more complicated, because, in the absence of buoyancy, phenomena that are masked in normal gravity assume great relevance [17].

The microgravity combustion science research conducted since the mid-1980s has significantly expanded the knowledge of the behavior of and resultant risk of a fire in the reduced gravity environment of a spacecraft [4, 13, 17, 18]. Still, given the complexity of fire, the development of an adequate fire safety strategy for spacecraft that will protect occupants, payload and vehicle requires the development of predictive tools that enable adequate prevention, optimized response and are validated at a scale that is representative of the phenomena [19, 20]. As such, it necessary to conduct realistic length and time-scale experiments under microgravity conditions for the following reasons:

1. Given the safety and operational related limitations, experiments have always been conducted as **individual** combustion tests. However, fire safety strategies require a system type validation that can only be achieved at a realistic scale, and one that not only determines the flame spread on the first ignited sample, but also on secondary samples.
2. **Buoyancy induced flows**, which dominate and mask numerous other physical processes in normal gravity flames, are particularly important in limit conditions associated with material

flammability testing (e.g. ignition and extinction). Prior work has shown that typical ventilation flow speeds in spacecraft are below those typical of fire-induced buoyant flows [1]. As a result, a spacecraft fire will most likely occur in flow conditions that cannot be readily duplicated on earth. Thus, extrapolation from large scale tests in normal gravity is currently not possible due to the lack of a **proper scaling** function.

3. All prior tests have been limited to samples that are no more than about 0.1 m in the longest **dimension**, and most of them were even smaller. Realistic fire geometries are substantially larger in scale (~ 0.5 m to 1.0 m) and involve coupled radiative and convective interactions between adjacent surfaces. Currently, there is no scaling rule that can adequately address the growth rate, pressure rise, radiative interaction, and the smoke build-up for a large microgravity fire. To establish such a rule or to have a validated numerical model, selected large scale tests are necessary.
4. The undesired effects of fires are linked to the rate of **heat and toxic product release** [21]. In most fires, the rate of heat release scales with the flame propagation rate, which is dependent on the oxygen supply rate to the combustion zone [21]. Further, the heat release rate from a solid material is a function of the gasification rate, which is strongly linked to the heat transfer within the solid and at the solid's surface [21]. As such, the geometry of the material matters and so does the material properties, the material thickness and the way the material is assembled [21]. Some examples of significant relevance are:
 - *Scale couplings defined by the geometrical characteristics of different materials:* Ignition, flame spread and burning of a homogenous material with a smooth flat surface can be different from the material response if the sample is a composite or has a non-flat surface [22, 23]. Changes from the tested material can include grooving, shaping, and addition of internal elements – both conductive and non-conductive. The impact of the geometry on the overall fire growth cannot be assessed unless the scale of the test increases to a size that will allow establishing the impact of these features and defining which features can be neglected.
 - *Property couplings defined by composite systems:* In spacecraft, most solid combustible materials are assembled along with non-combustible materials with high thermal conductivity (the so-called “systems with added enthalpy”). In the absence of buoyant convection, such added thermal conductivity could result in significant variation of the flame propagation velocity, as compared to the results from the test conditions where such added enthalpy is not present. In order to close the existing gap in our knowledge

of these processes, a series of successive studies on combustion of small and large scale samples and studying the role of collective effects and added heat conductivity in strongly encumbered spaces have to be undertaken.

5. Modelling tools developed for quantitative assessment of the performance of fire safety systems need validation that takes all the issues described above into account [19]. In most cases, modelling tools need to include complex numerical simulation software that can predict ignition and combustion of materials in a strongly encumbered space, which contains composite materials and incorporates combustible and heat conducting components. Given the mentioned buoyancy and length scale dependent phenomena, such a tool can only be validated with experiments in microgravity at a scale that encompasses all the relevant details.

The path towards a quantitative integration of fire safety in the design and management of spacecraft will be approached through the *Saffire* experimental series, which comprises fire experiment of realistic scale and complexity in micro-gravity. The experiment and analysis will cover the main issues associated with this process and are as follows:

- **Prevention through material selection:** The cornerstone of fire prevention is the adequate characterization of materials [13, 24, 25]. In summary, the flammability focus of *Saffire* 1-3 will be on isolating relevant physical parameters, establishing their dependency on the test environments, and determining the relationship between them such that future testing results are indicative of safety in the actual operational environment. Such improved understanding of material flammability was endorsed in a recent review by the National Research Council [3]. Ultimately, this work could support moving away from screening and into a method that establishes a targeted assessment of material flammability and intrinsic material properties that can be used in active systems to extrapolate real fire behavior.
- **Scale Dependent Sensitivity:** NASA-STD-6001 Test 1 [26, 27] is based on a single criterion, which is self-propagation. However, it is well known that radiative heating from a nearby surface greatly affects the energy balance and, thus, modify the self-propagation thresholds [28-30]. Given the nature of both radiative and convective heat transfer, these phenomena are strongly scale dependent. The current project has as specific objective to capture the effect of the complex scale dependent phenomena at relevant length scales.
- **Fundamental Predictive Modelling:** Currently, there are no validated predictive models available for microgravity fires that encompass all the relevant phenomena, thus one of the most

relevant and lasting outcomes of these experiments is to provide validation data for fire model development. The large-scale microgravity fires will be used to support the verification of large scale microgravity fire modelling, an effort that was endorsed by the National (US) Research Council Committee on Microgravity Research [3, 31]. The present research program integrates state of the art computational tools to develop specifically tailored models for microgravity fire growth. The experiments aim to obtain the necessary data to mature and verify these models. The experiments will also provide system data that will enable assessment of the models' performance when attempting to predict system behavior.

Experimental Description

The design goal for the *Saffire* experiment series was that the hardware would be more or less identical in the three units, apart from the sample materials to be burned. The experimental module to be brought on as cargo on Orbital Sciences' *Cygnus* consists of a flow duct and an adjacent avionics bay, as seen in Fig. 1. The flow duct forms the primary chamber of the experiment while the avionics bay is connected to the side of the flow duct as shown in the figure. A LexanTM panel forms the wall between the flow duct and the avionics bay. Air is drawn through the flow duct by fans located at the top of the duct with flow straighteners at the bottom of the experiment module. The flow duct/avionics bay assembly is a rigid structure and will be secured with the standard stowage straps used in the *Cygnus* vehicle. This duct will provide a uniform flow across the samples, maintain a clear flow path within the experiment module, and prevent burning debris from interacting with the rest of the cargo.

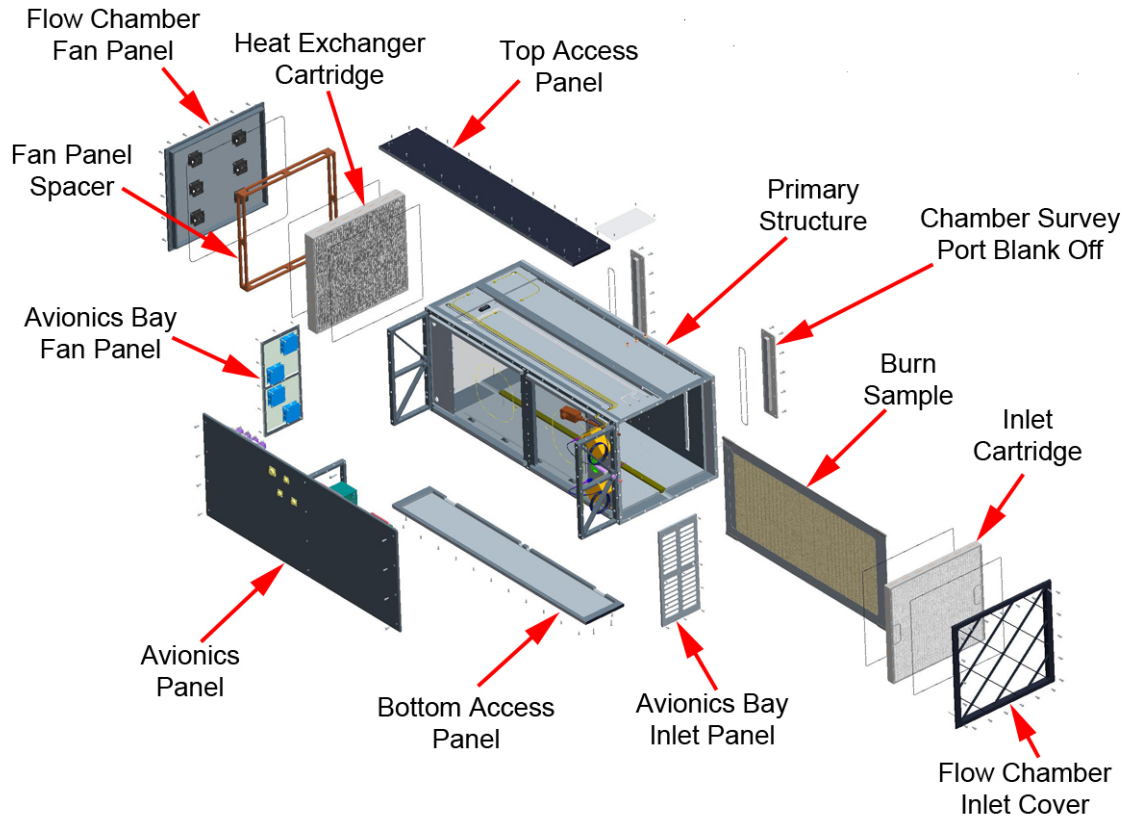


Figure 1: Schematic of separated module for the *Saffire* experiments with all the main parts labeled.

In order to exploit the unique experimental environment that the *Cygnus* vehicle offers, *Saffire 1* will burn a large sample of a cotton-fiberglass blend having an area density of 18.2 mg/cm^2 . This is referred to as “SIBAL” fabric because it was originally developed for use by the Solid Inflammability Boundary at Low Speed experiment [32]. This composite fabric consists of about 75% cotton and 25% inert fiberglass by weight. The thickness of the fuel sample is 0.3175 mm. This material has the advantage of maintaining its structural integrity even after the cotton has been consumed, allowing the measurement of the char front and avoiding the tears and curling common with thin fuels. In addition to the data obtained through the cameras, 6 surface thermocouples will measure the surface temperature and the temperature just above the sample surface. Figure 2 provides an overview of the SIBAL sample that will be burned in *Saffire 1*. As such, the experiment will provide data for a charring material burning at nominal spacecraft ventilation flow (see Table 1). Thus, it can be compared with BASS data (experiments on board the International Space Station) at 1 and 2 cm width [33], and the *Saffire 2* flight samples.

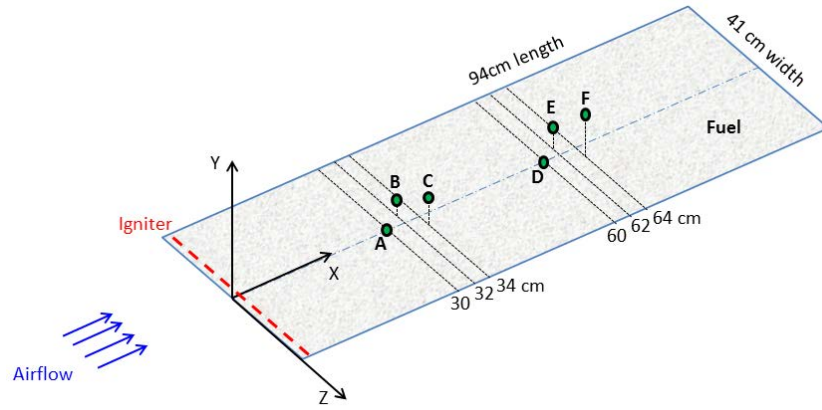


Figure 2: Flame and fuel surface temperature measurement locations for the large sample to be flown on *Saffire* 1 and 3. Thermocouples B, C, E, and F are slightly off the centerline. Thermocouples B and C are 8 and 10 mm above the surface, respectively. The downstream thermocouples E and F are respectively 8 and 25 mm above the surface.

Table 1: Overview of the *Saffire* 1 experiment.

Sample #	Material	Sample Thickness	Flow (cm/s)	Igniter Position
<i>Saffire</i> 1	SIBAL	Standard	20	Bottom

Figure 3 shows the sample placed in the flow duct (left) and a schematic of the full assembly (right).

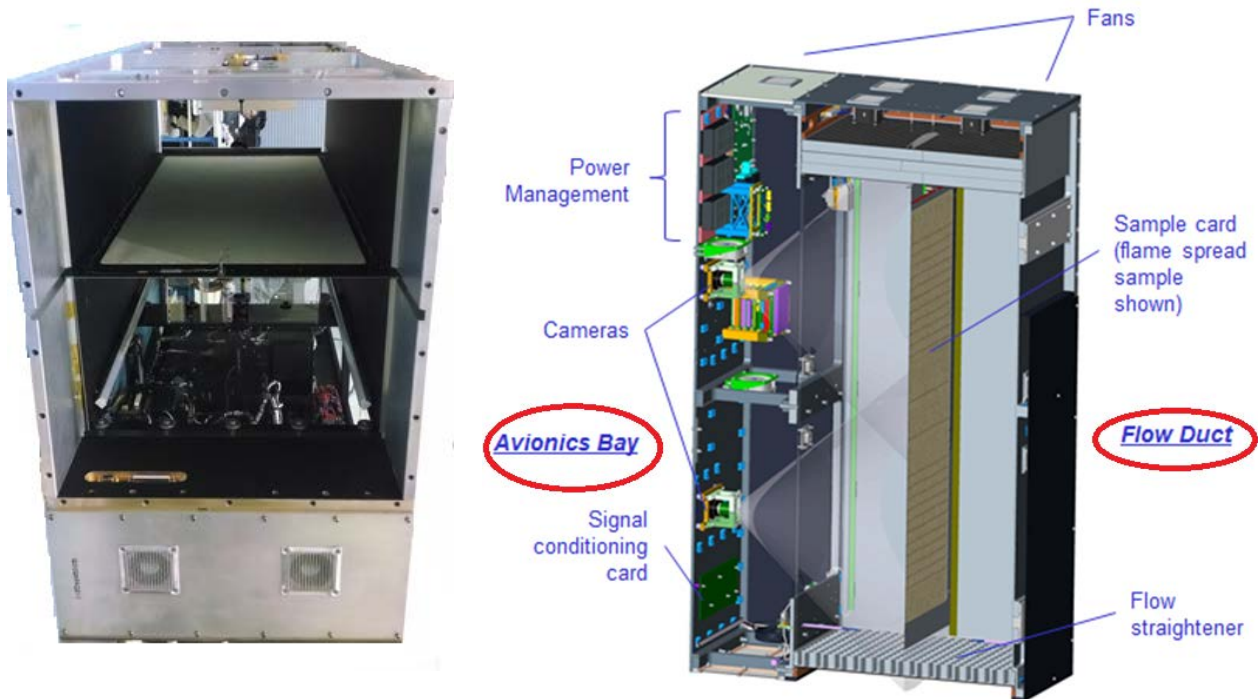


Figure 3: A picture of the large sample to be burned in *Saffire*-1 placed in the experimental module (left) and its placement in the assembled module (right). The sample is 41 cm wide by 94 cm long.

The experimental objectives for *Saffire 2* focus on material selection and comparison with NASA Test-1. Therefore, four different materials will be tested during this flight: SIBAL, PMMA, NOMEX and silicone. In addition, one silicone sample will be tested in opposed flow, and one PMMA sample will have a structured surface. The silicone provides a material that just barely passes NASA Test-1 in normal gravity, and will thus provide information on whether or not the material flammability and flame spread is more severe in 1g or μg . In air at normal gravity, upward flame spread, the 0.25 mm (0.10”) silicone has been tested at NASA Glenn Research Center, and it burns an average of 27.4 cm (10.8”) with most of the samples burning completely. The 0.36 mm (0.014”) silicone burns an average of 14.7 cm (5.8”) and the 0.61 cm (0.024”) thick silicone burns an average of 7.6 cm (3.0”). In the downward configuration the 0.36 mm (0.014”) silicone burns completely (unlike the upward configuration). The SIBAL samples provide benchmarking between the different flight experiments and also scaling between the large and the small samples. Finally, one sample will be NomexTM, which is a flame resistant material that is used commonly as a fire stop on spacecraft. This sample is not expected to burn even though a short segment of PMMA will be at the leading edge to promote ignition. Figure 4 shows an overview of the samples to be tested in *Saffire 2* (left) along with the actual sample card for the flight (right).

One of the concerns for fire safety in spacecraft is that structured materials, which are commonly used in space vehicles and infrastructure, will behave much differently than the perfectly smooth samples that are typically used in scientific experiments. The University of Bremen has focused on structured materials in the development of one of the sample materials for *Saffire 2*, and this has involved the use of the drop tower facilities at ZARM. The work followed the procedures of NASA-Test 1. Figure 5 shows the results for the ratio of the spread velocity between a structured PMMA sample and a flat PMMA sample, both burned in normal gravity. It is seen that the structured sample could reach more than twice the spread velocity of the flat sample [22]. Figure 6 shows IR images for different structure types (see base of figure for the structure shape). All the pictures are taken after 60 seconds, and the figure clearly shows that the spread velocity is significantly different for the various structure shapes.

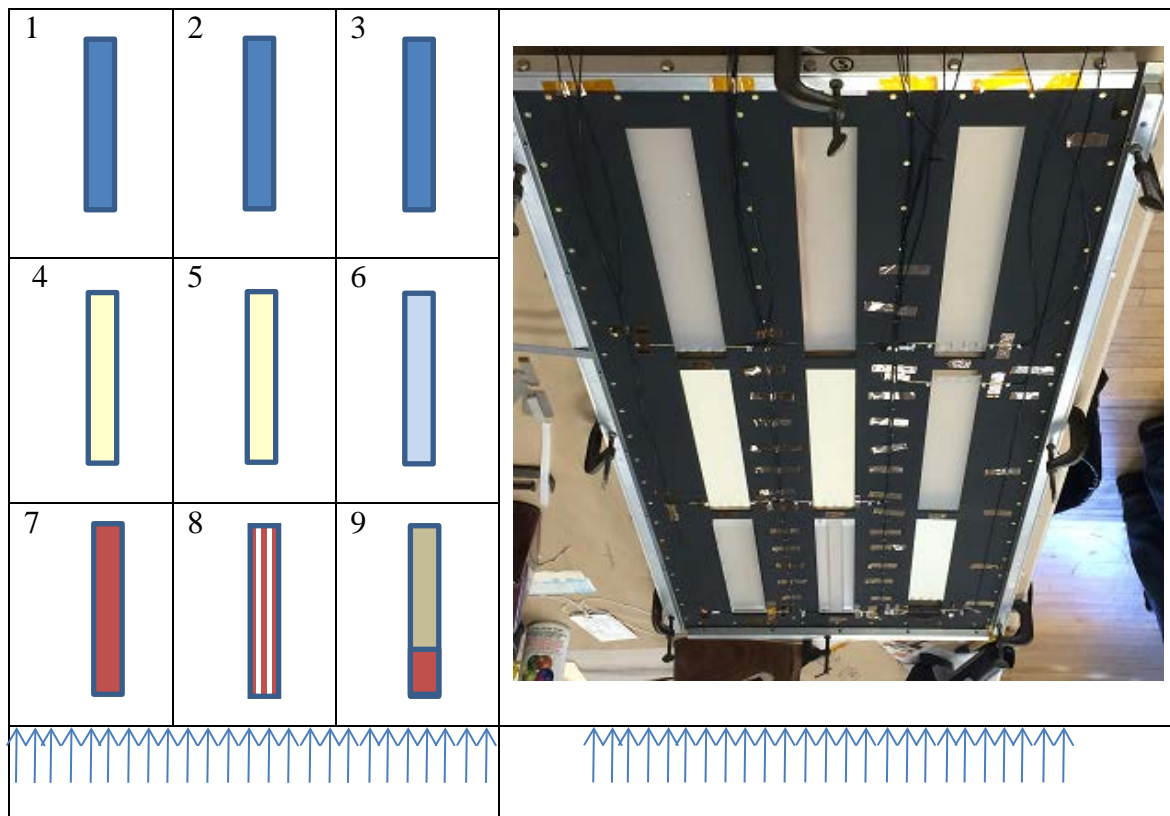


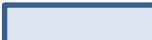
Figure 3: The samples to be burned in *Saffire 2* (left) and the sample card with samples in place (right). The sample materials in the top row are silicone of different thicknesses. The materials in the middle row are, from left to right: Sibal, Sibal, opposed flow silicone. In the lower row, from left to right, the samples are: flat PMMA, structured PMMA, and Nomex with PMMA ignition segment. Each of the 9 samples in the array is 5 cm by 30 cm.

PMMA: 

SIBAL: 

Nomex: 

Silicone: 

Silicone #2 opposed: 

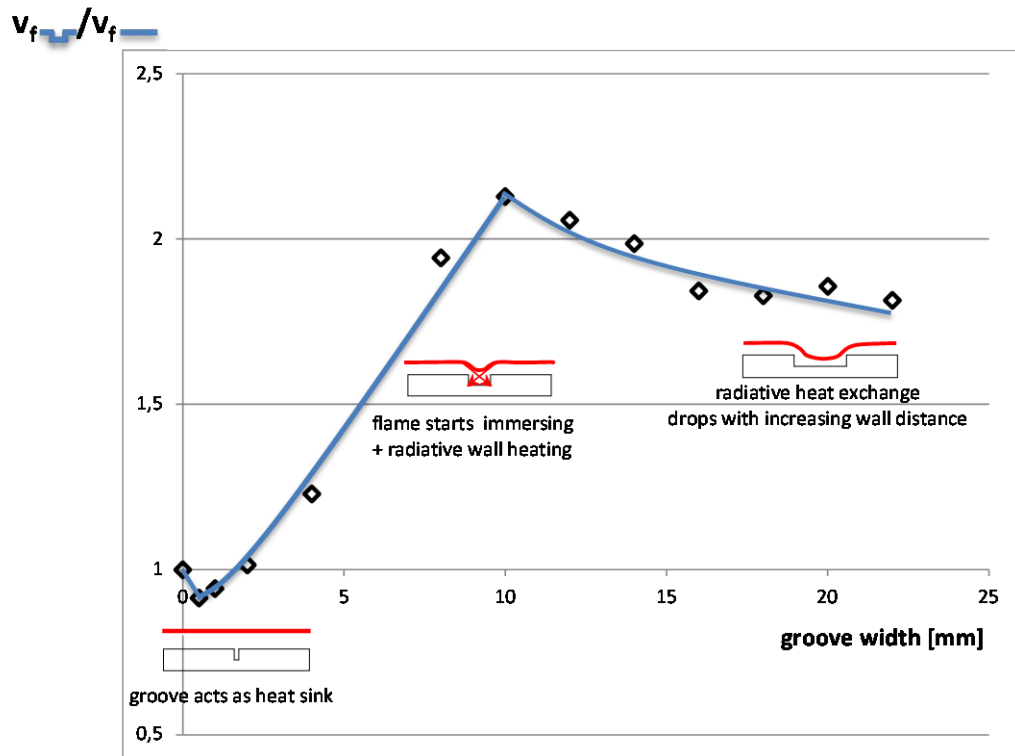


Figure 5: Vertical relative flame propagation velocity (in normal gravity, 1g) along grooved PMMA samples of 300 x 65 x 10 mm. The groove depth is 5 mm. The results are related to a flat plate according to NASA Test 1 [34].

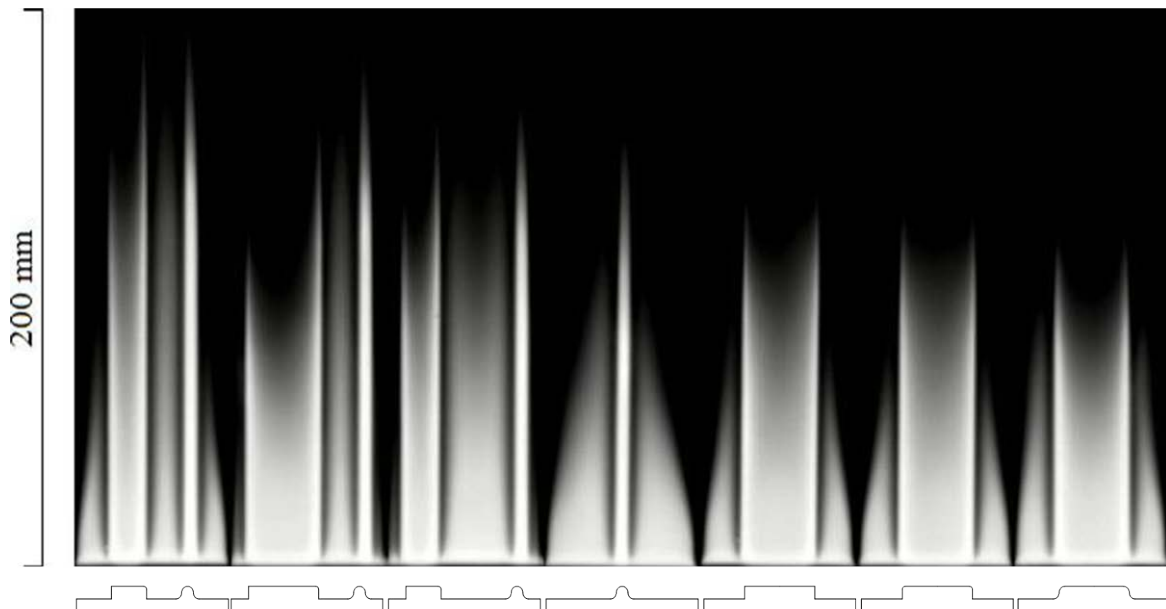


Figure 6: IR-images of the damage front during vertical flame propagation along surface-structured PMMA samples (1g). All images were taken after 60 s [22].

As the results from the tests at ZARM clearly indicate the significant differences in mass burning rates and flame spread rates for the three samples, one sample on *Saffire 2* (*Saffire-2-S8*, see the sample and its placement in Fig. 3) will contain a PMMA slab that is machined to produce grooves with different edge curvatures similar to the work in Fig. 7.

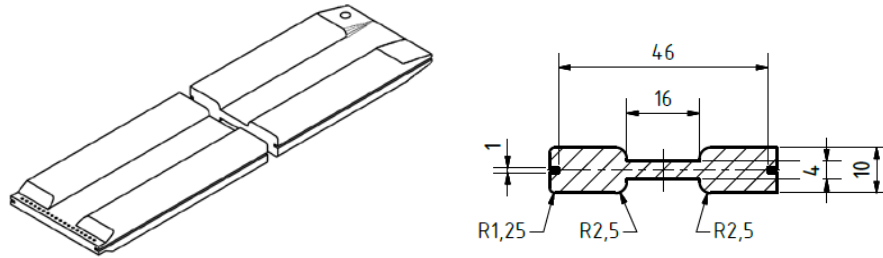


Figure 7: Structured PMMA sample. Oblique view (left) and structure cross section details (right). The sample is 300 mm long and 50 mm wide. All dimensions are in mm.

Table 2 summarizes the experimental settings for *Saffire 2*.

Table 2: Overview of the *Saffire 2* experiment.

Sample #	Material	Sample Thickness	Flow (cm/s)	Igniter Position
<i>Saffire-2-S1</i>	Silicone	0.25 mm (0.010") (Flammability limit 1)	20 (Concurrent)	Bottom
<i>Saffire-2-S2</i>	Silicone	0.36 mm (0.014") (Flammability limit 2)	20 (Concurrent)	Bottom
<i>Saffire-2-S3</i>	Silicone	0.61 mm (0.024") (Flammability limit 3)	20 (Concurrent)	Bottom
<i>Saffire-2-S4</i> (Compares with <i>Saffire-1</i>)	SIBAL	Standard	20 (Concurrent)	Bottom
<i>Saffire-2-S5</i> (Compares with <i>Saffire-3</i>)	SIBAL	Standard	Velocity of <i>Saffire-3</i> (30) (Concurrent)	Bottom
<i>Saffire-2-S6</i>	Silicone	0.36 mm (0.014") Silicone	20 (Opposed)	Top
<i>Saffire-2-S7</i>	PMMA	6 mm with tapered edge for ignition	30 (Concurrent)	Bottom
<i>Saffire-2-S8</i>	PMMA	Structured PMMA with tapered edge for ignition	20 (Concurrent)	Bottom
<i>Saffire-2-S9</i>	PMMA and NOMEX	N/A Transition from PMMA to NOMEX	20 (Concurrent)	Bottom

The current experimental configuration has a limited camera capability with no side view. Therefore, in *Saffire 2* two thermocouples are spaced as detailed in Fig. 8 in the SIBAL (shown) and Nomex samples in order to capture the flame location and standoff distance.

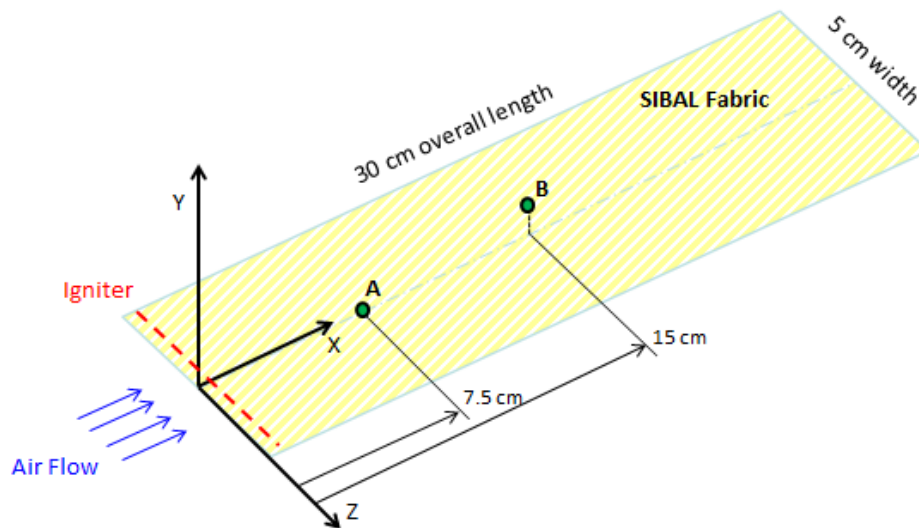


Figure 8: A detailed view of *Saffire 2* sample number 7, showing the two thermocouples (A and B) used for measuring temperature profiles, which can be used to establish flame location and flame standoff distance.

The flow settings in *Saffire 3* will be determined after the data from *Saffire 1* have been analyzed. Table 3 shows the preliminary overview of *Saffire 3* and, as indicated, there are three options for the flow.

Table 3: Preliminary overview of the *Saffire 3* experiment.

Sample #	Material	Sample Thickness	Flow (cm/s)	Igniter Position
<i>Saffire-3-A1</i>	SIBAL	Standard	Higher than <i>Saffire 1</i>	Bottom
<i>Saffire-3-A2</i>	SIBAL	Standard	20 (repeat <i>Saffire 1</i>)	Bottom
<i>Saffire-3-A3</i>	SIBAL	Standard	Lower than <i>Saffire 1</i>	Bottom

Conclusion

Predicting the end state of an unconstrained fire in a spacecraft and validating NASA's flammability test methods are probably the areas of greatest uncertainty in our effort to ensure the fire safety of future spacecraft. These questions are being addressed in the experiments being developed for *Saffire 1-3*, which will be the first of their kind to evaluate low-g material flammability with direct implications for fire safety on future exploration vehicles. The material

flammability experiments that are to be conducted on Orbital's *Cygnus* vehicle after it has de-berthed from the ISS and before it re-enters the atmosphere will be undertaken in a habitable pressurized environment of considerable size without the hazards associated with a crewed vehicle. This opportunity enables the study of practical low-g material flammability phenomena that are important for spacecraft design yet cannot be studied in ISS facilities or other orbital platforms.

The *Saffire* experiment series will be a landmark for spacecraft fire safety with the data and subsequent analysis providing much needed verifications of spacecraft fire safety protocol for the crews of future exploration vehicles and habitats. Furthermore, the experiment contents for follow-on flights that address other questions and needs in spacecraft fire safety are being developed. The *Saffire* hardware and the *Cygnus* vehicle provide a unique opportunity to demonstrate other fire safety technologies including fire detection, fire suppression, post-fire clean-up, and monitoring. These follow-on experiments to the first *Saffire* flights could address questions such as how much fire suppressant is required to extinguish a plausible spacecraft fire, or how much sorbent material is required to clean up a habitable volume in a specified period of time following a fire? These questions and the associated technologies are being evaluated by NASA fire safety stakeholders to formulate up to three additional flights on *Cygnus* (*Saffire* 4-6).

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